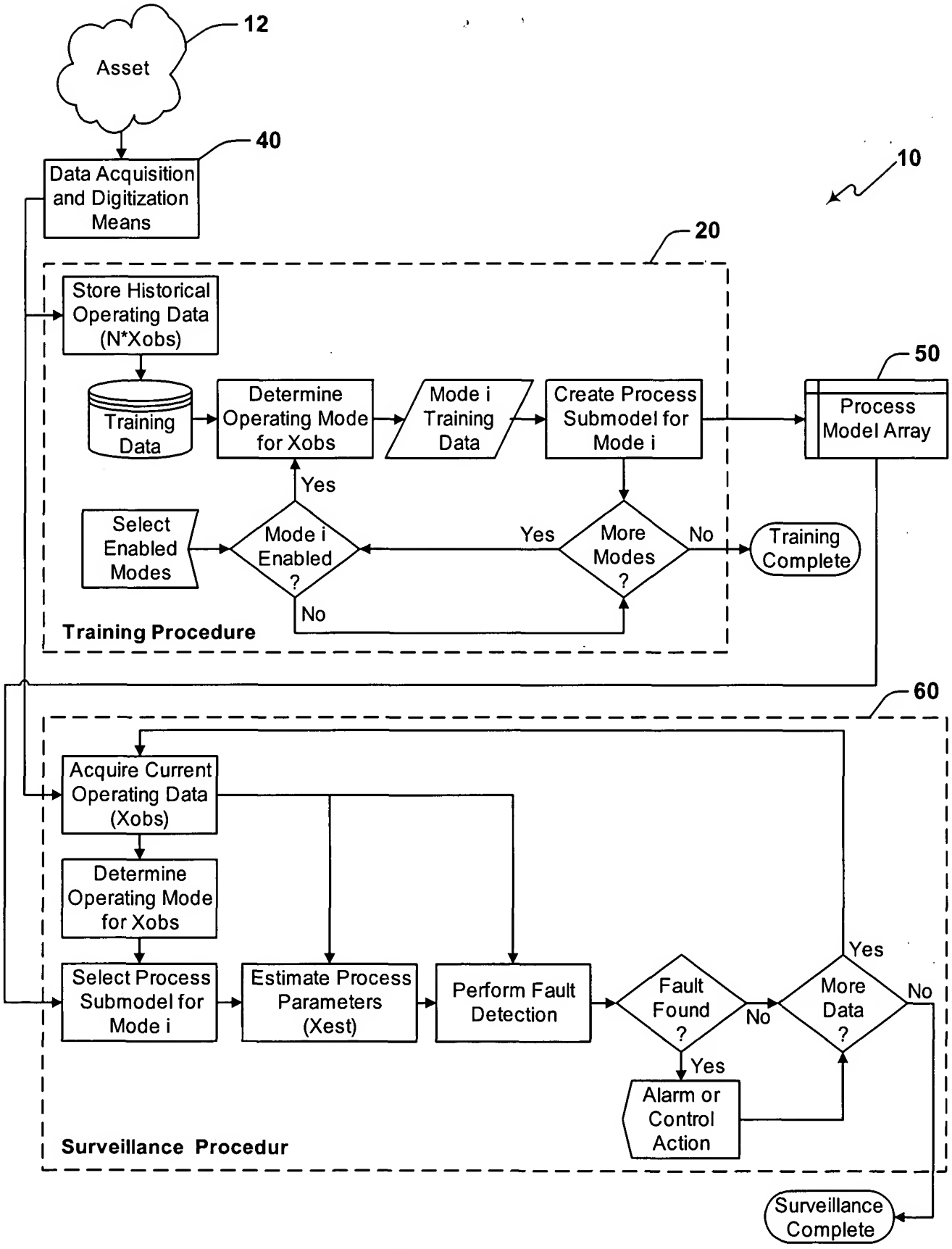
12
Asset
40
Data Acquisition and Digitization Means
10
20
Store Historical Operating Data (N*Xobs)
Training Data
Determine Operating Mode for Xobs
Mode i Training Data
Create Process Submodel for Mode i
50
Process Model Array
Yes
Select Enabled Modes
Mode i Enabled ?
Yes
More Modes ?
No
Training Complete
No
Training Procedure
60
Acquire Current Operating Data (Xobs)
Determine Operating Mode for Xobs
Select Process Submodel for Mode i
Estimate Process Parameters (Xest)
Perform Fault Detection
Fault Found ?
No
More Data ?
Yes
No
Yes
Alarm or Control Action
Surveillance Procedur
Surveillance Complete

Figure 1

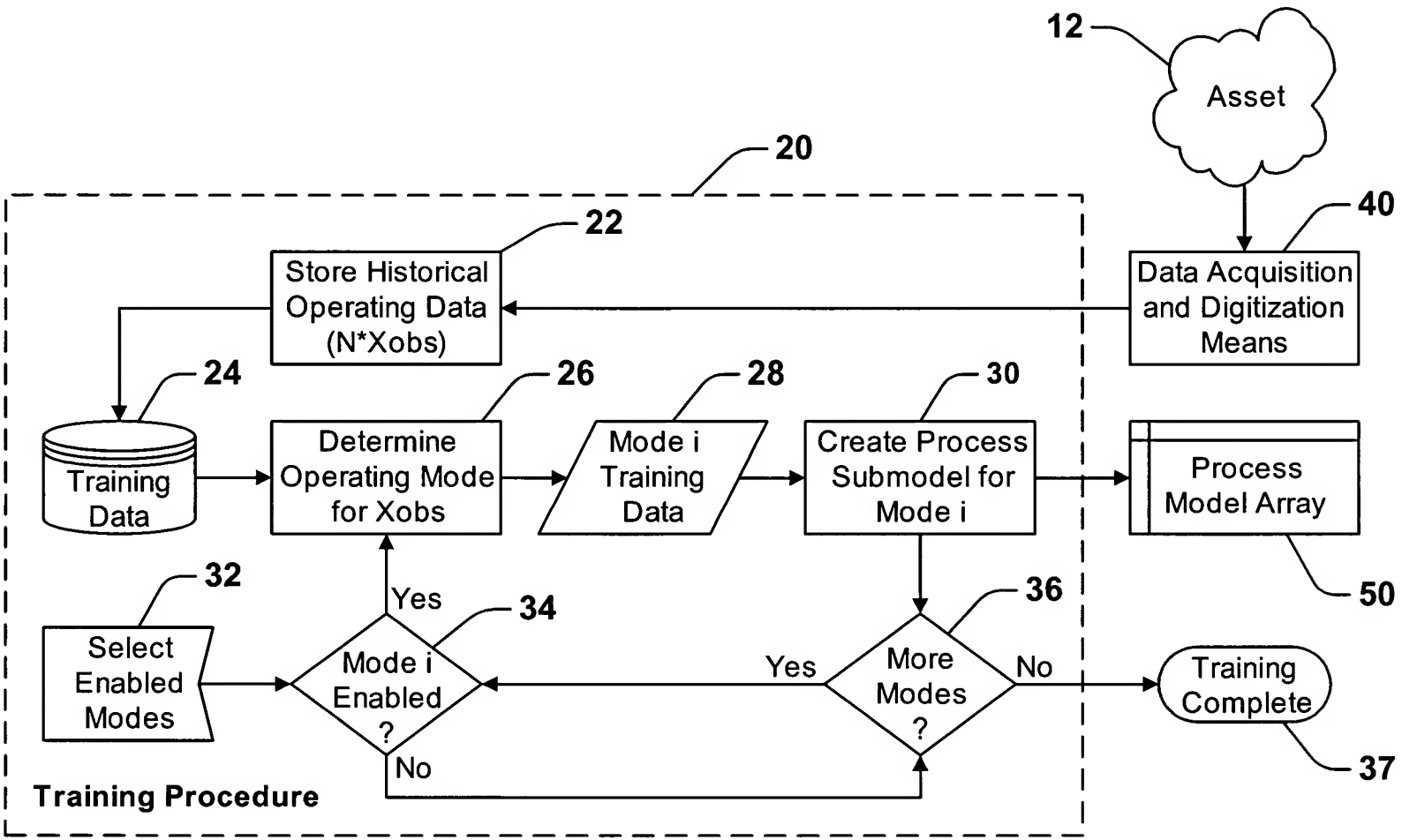
12
Asset
20
22
Store Historical Operating Data (N*Xobs)
40
Data Acquisition and Digitization Means
24
26
28
30
Training Data
Determine Operating Mode for Xobs
Mode i Training Data
Create Process Submodel for Mode i
Process Model Array
50
32
Yes
34
36
Select Enabled Modes
Mode i Enabled ?
Yes
More Modes ?
No
Training Complete
37
No
Training Procedure

Figure 2

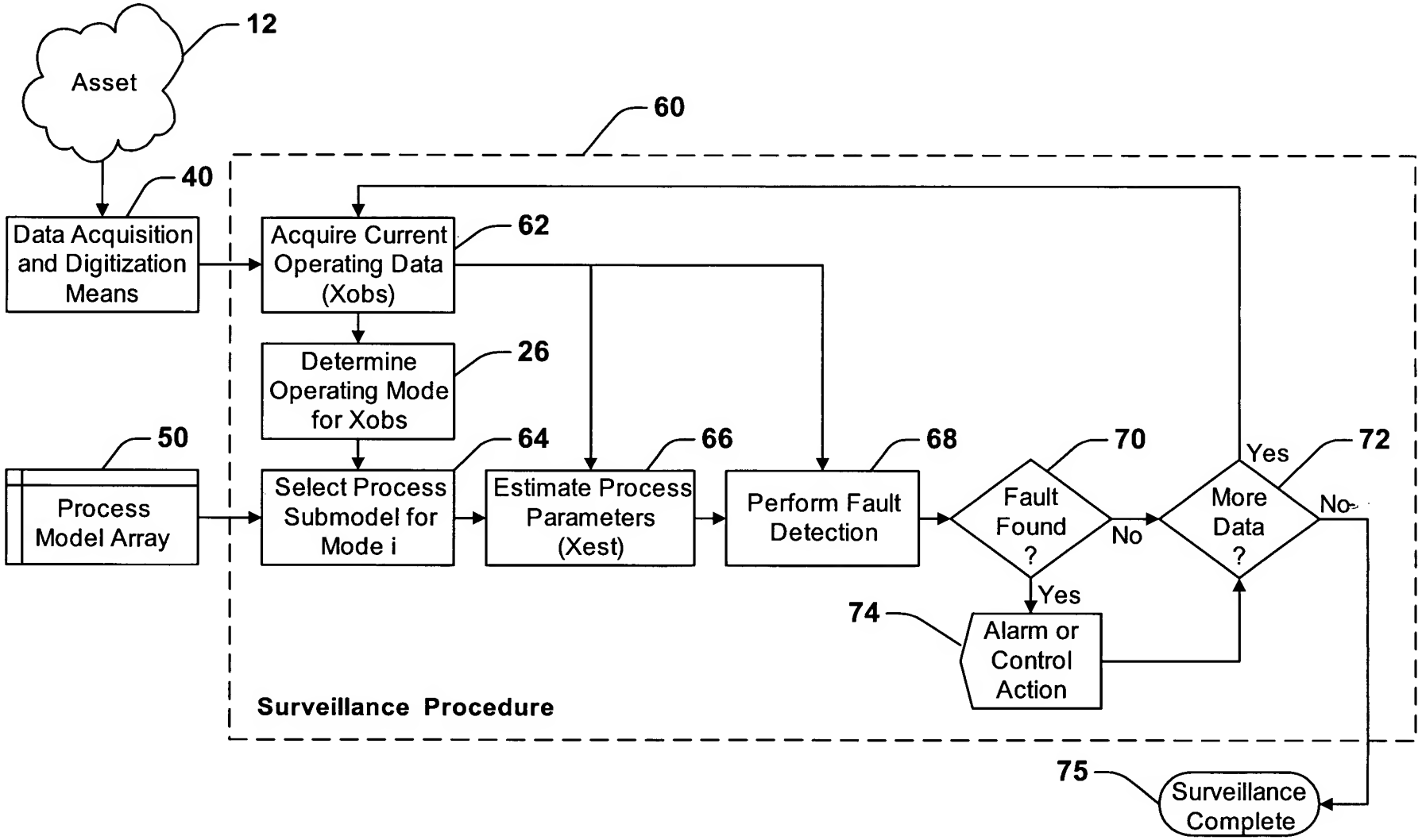
12
Asset
60
40
Data Acquisition and Digitization Means
Acquire Current Operating Data (Xobs)
62
Determine Operating Mode for Xobs
26
50
Process Model Array
64
Select Process Submodel for Mode i
66
Estimate Process Parameters (Xest)
68
Perform Fault Detection
70
Fault Found ?
No
Yes
72
More Data ?
Yes
No
74
Alarm or Control Action
Surveillance Procedure
75
Surveillance Complete

Figure 3

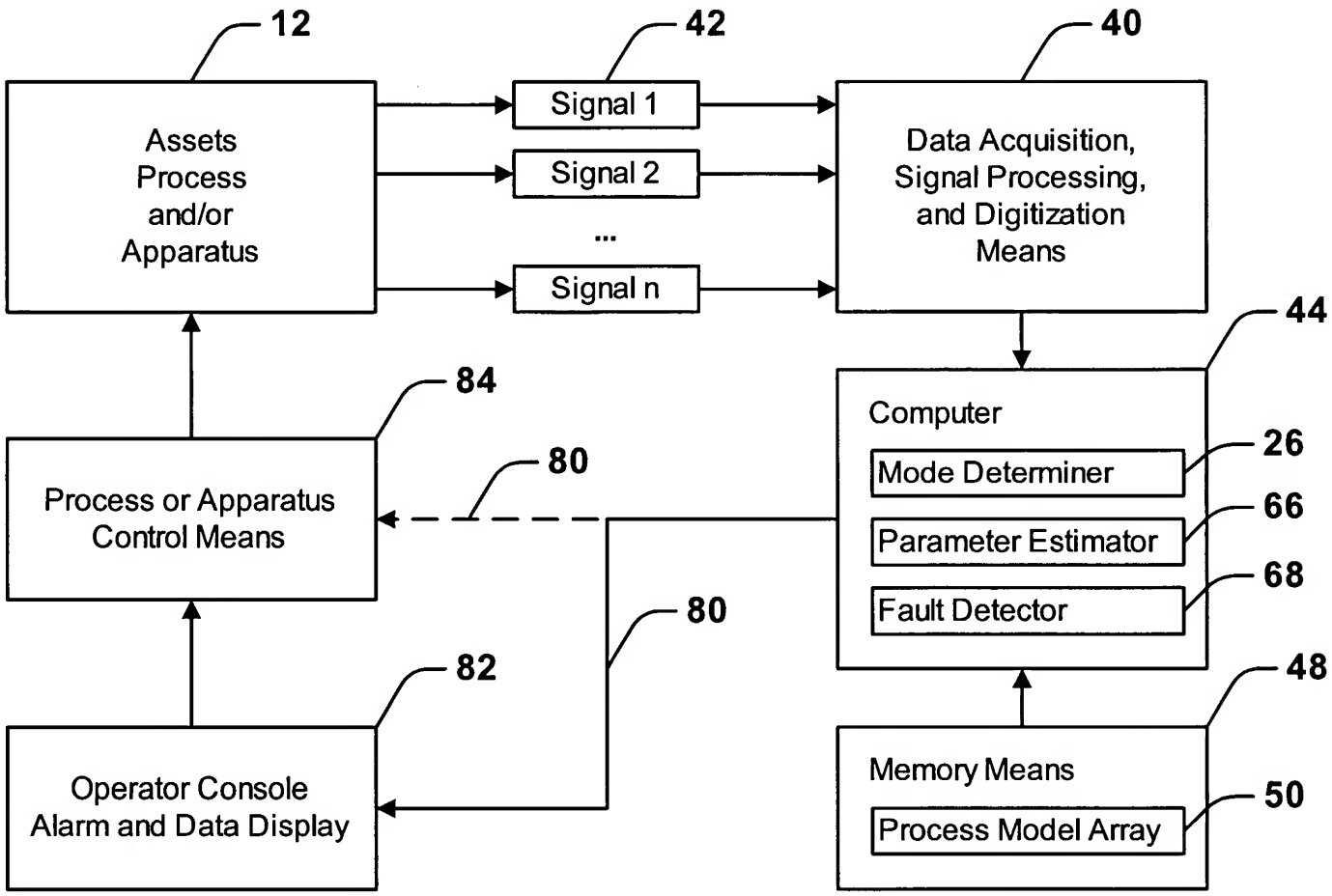
12
42
40
Assets Process and/or Apparatus
Signal 1
Signal 2
...
Signal n
Data Acquisition, Signal Processing, and Digitization Means
44
84
Computer
80
Mode Determiner
26
Process or Apparatus Control Means
Parameter Estimator
66
Fault Detector
68
80
82
48
Memory Means
Operator Console Alarm and Data Display
Process Model Array
50

Figure 4

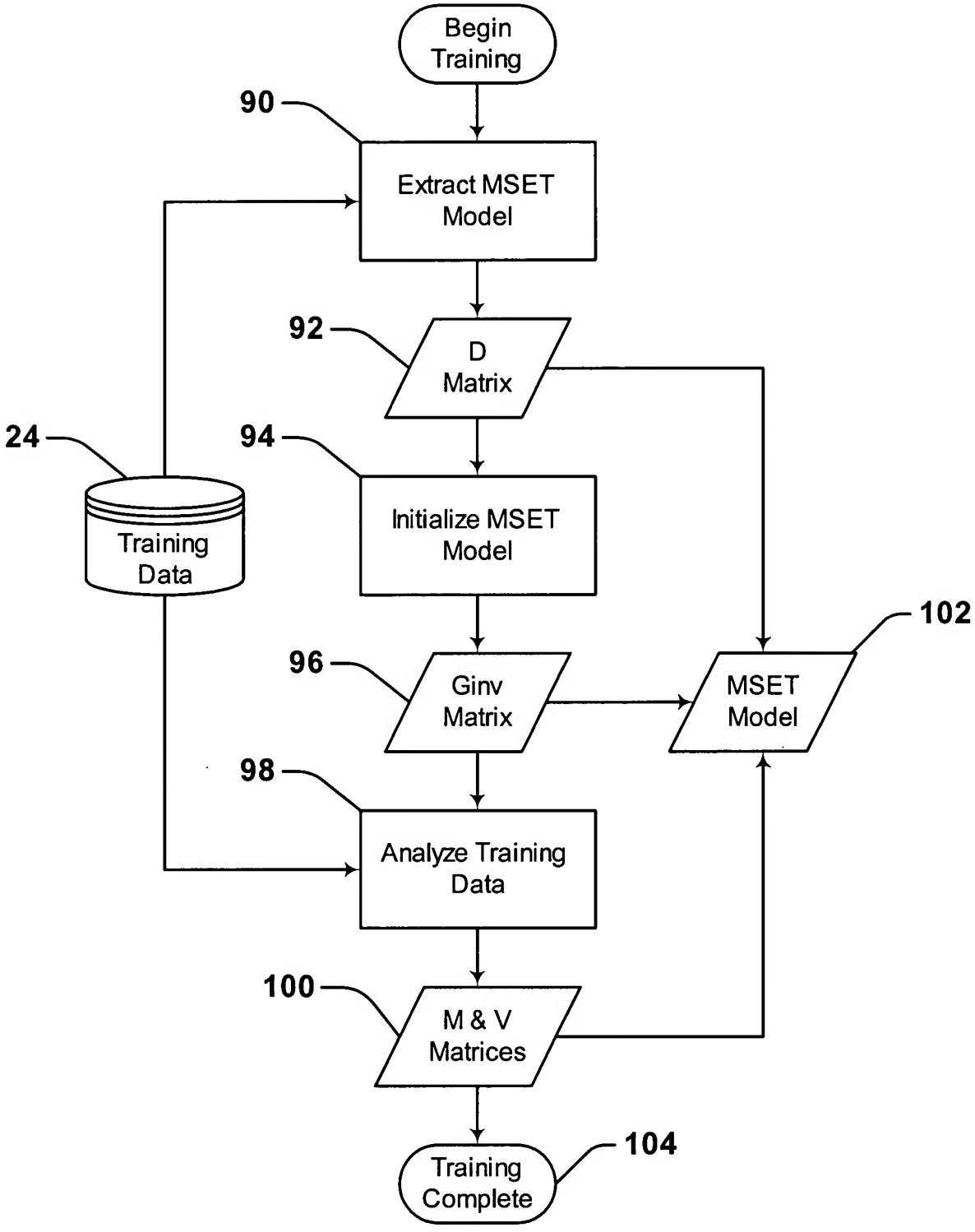
Begin Training
90
Extract MSET Model
92
D Matrix
24
94
Training Data
Initialize MSET Model
102
96
Ginv Matrix
MSET Model
98
Analyze Training Data
100
M & V Matrices
Training Complete
104

Figure 5

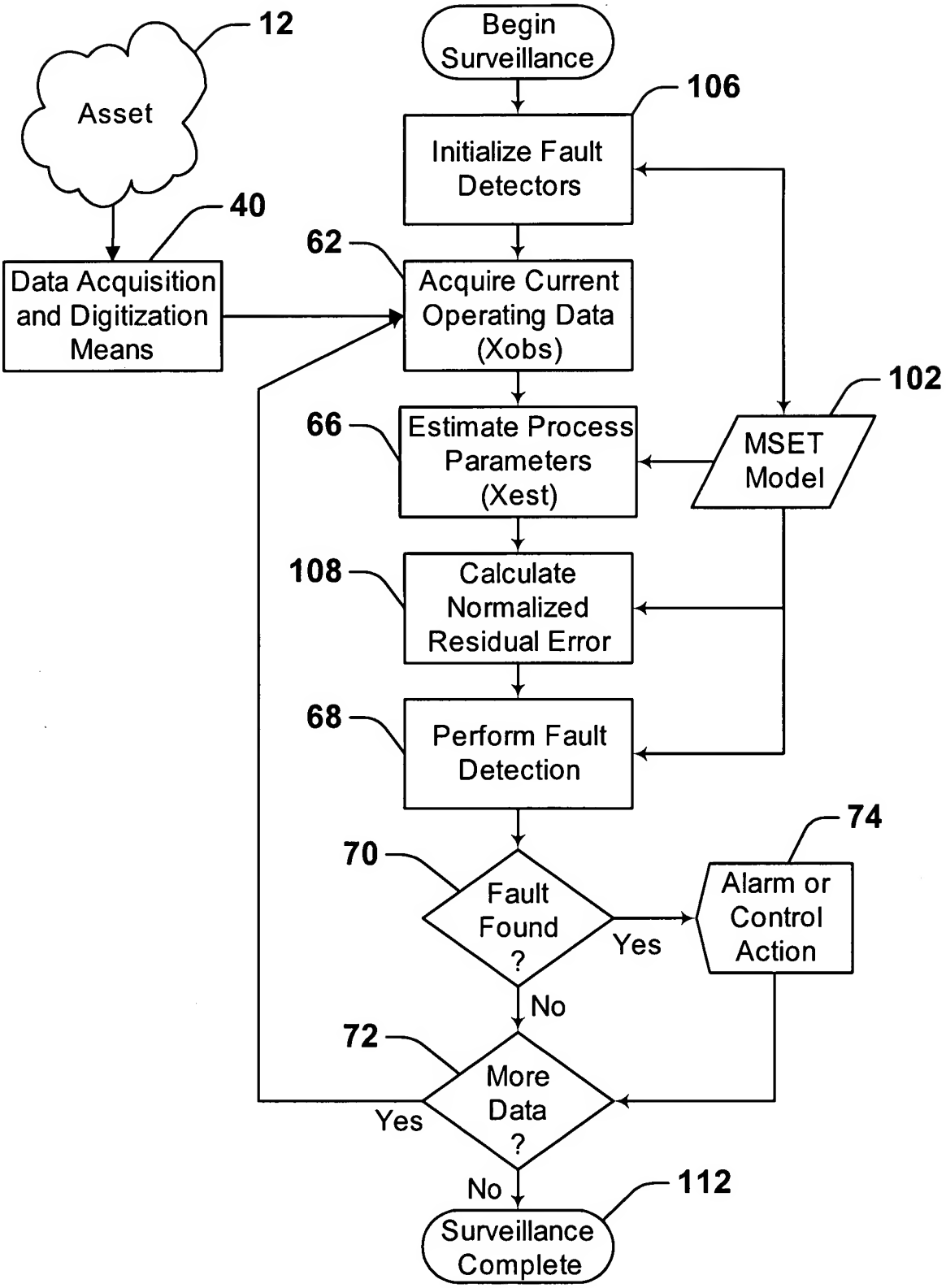
12
Asset
40
Data Acquisition and Digitization Means
Begin Surveillance
106
Initialize Fault Detectors
62
Acquire Current Operating Data (Xobs)
102
MSET Model
66
Estimate Process Parameters (Xest)
108
Calculate Normalized Residual Error
68
Perform Fault Detection
74
70
Fault Found ?
Yes
Alarm or Control Action
No
72
More Data ?
Yes
No
112
Surveillance Complete

Figure 6

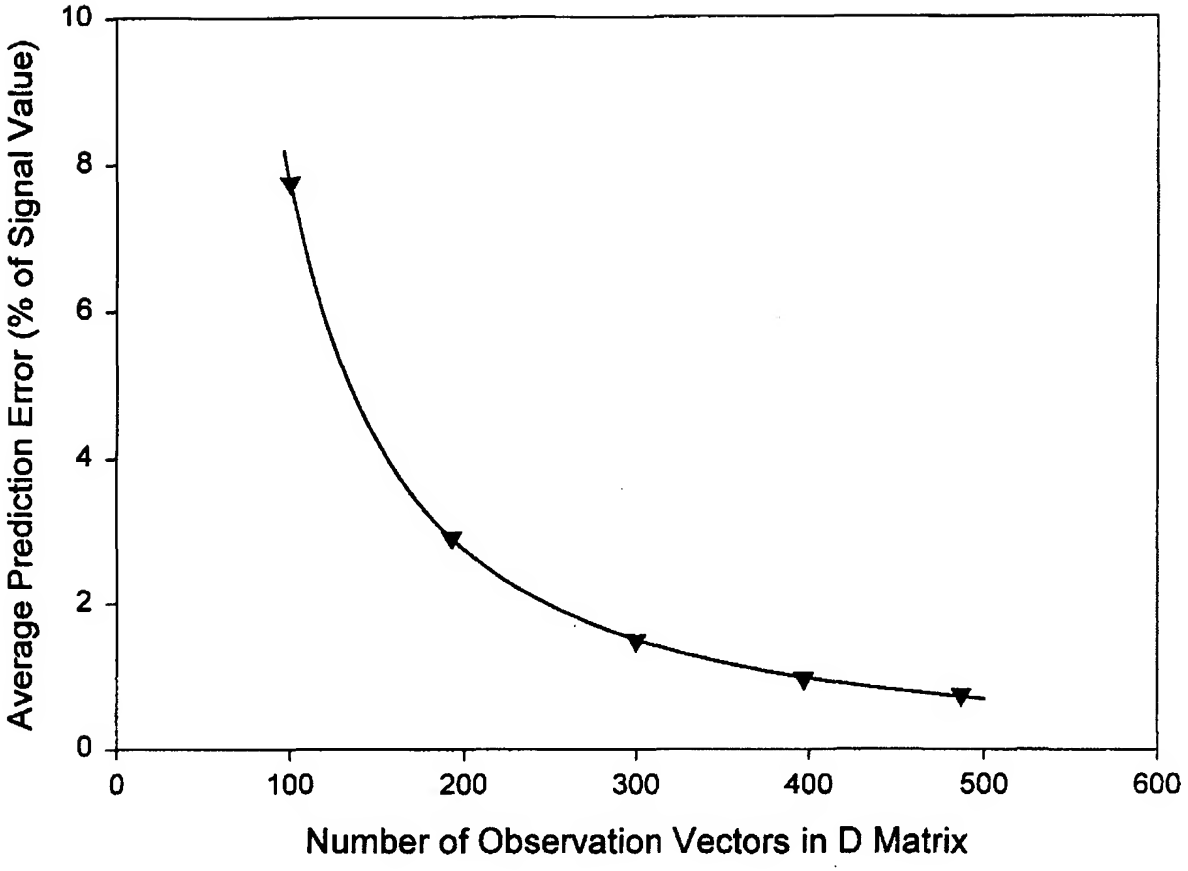
Average Prediction Error (% of Signal Value)
10
8
6
4
2
0
0
100
200
300
400
500
600
Number of Observation Vectors in D Matrix

Figure 7

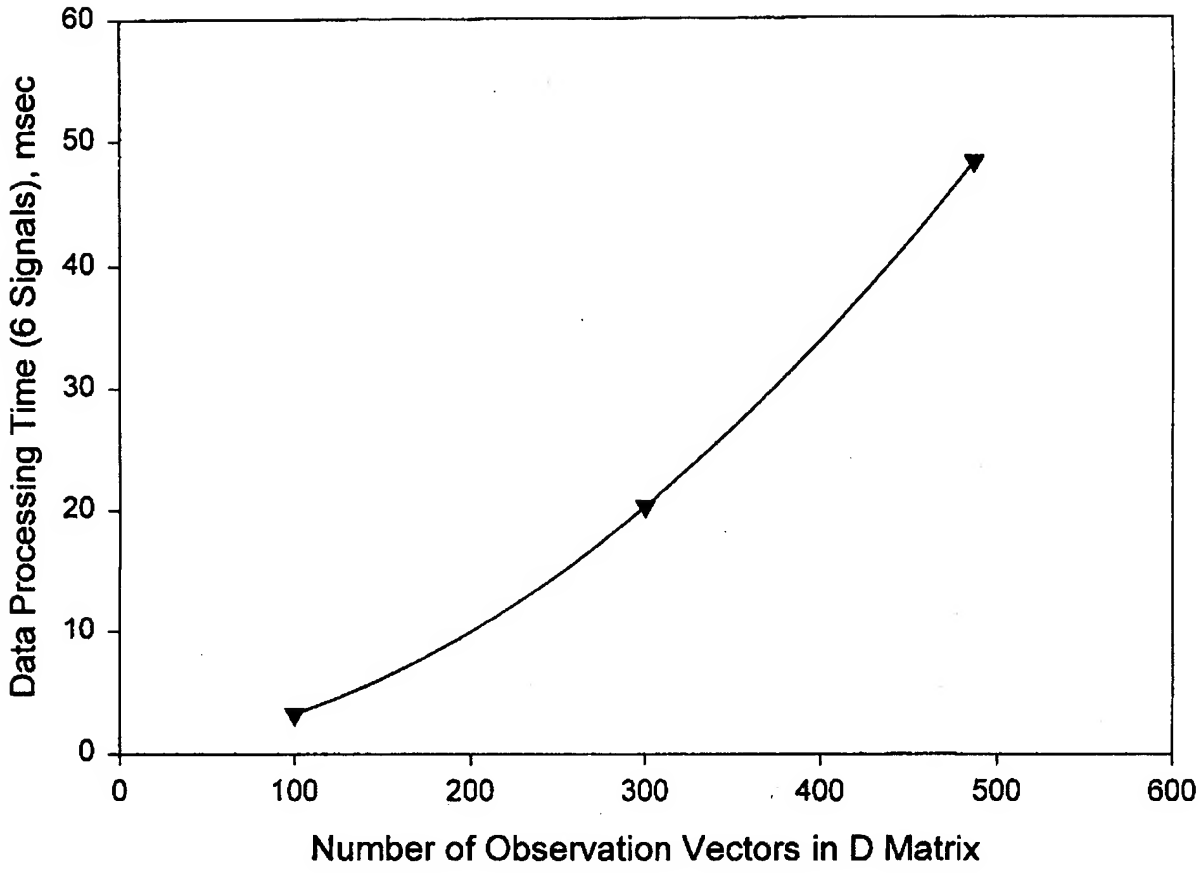
Data Processing Time (6 Signals), msec
60
50
40
30
20
10
0
0
100
200
300
400
500
600
Number of Observation Vectors in D Matrix

Figure 8

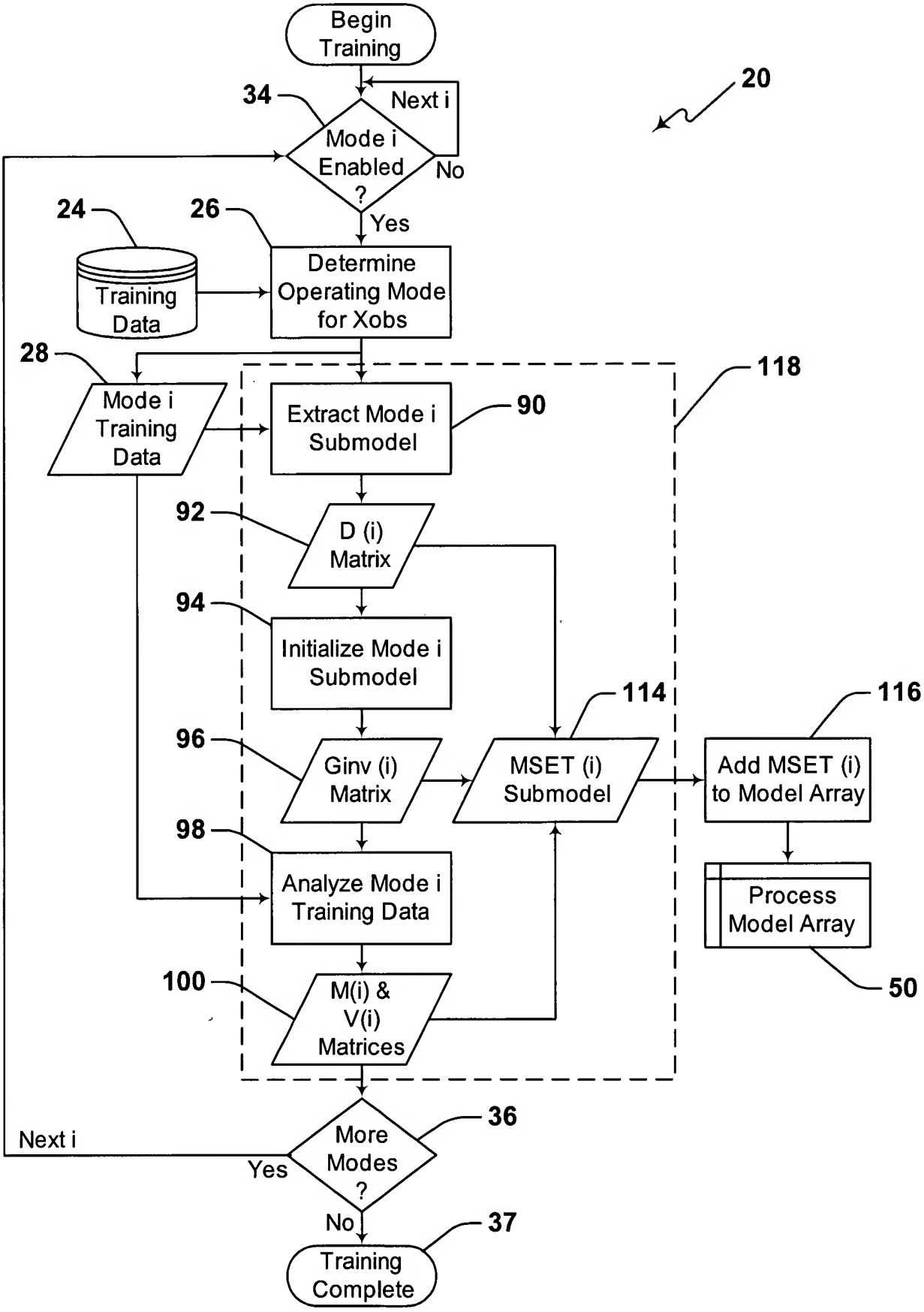
Begin Training
20
34
Next i
Mode i Enabled ?
No
Yes
24
26
Training Data
Determine Operating Mode for Xobs
28
Mode i Training Data
118
Extract Mode i Submodel
90
92
D (i) Matrix
94
Initialize Mode i Submodel
114
116
96
Ginv (i) Matrix
MSET (i) Submodel
Add MSET (i) to Model Array
98
Analyze Mode i Training Data
Process Model Array
50
100
M(i) & V(i) Matrices
36
Next i
More Modes ?
Yes
No
37
Training Complete

Figure 9

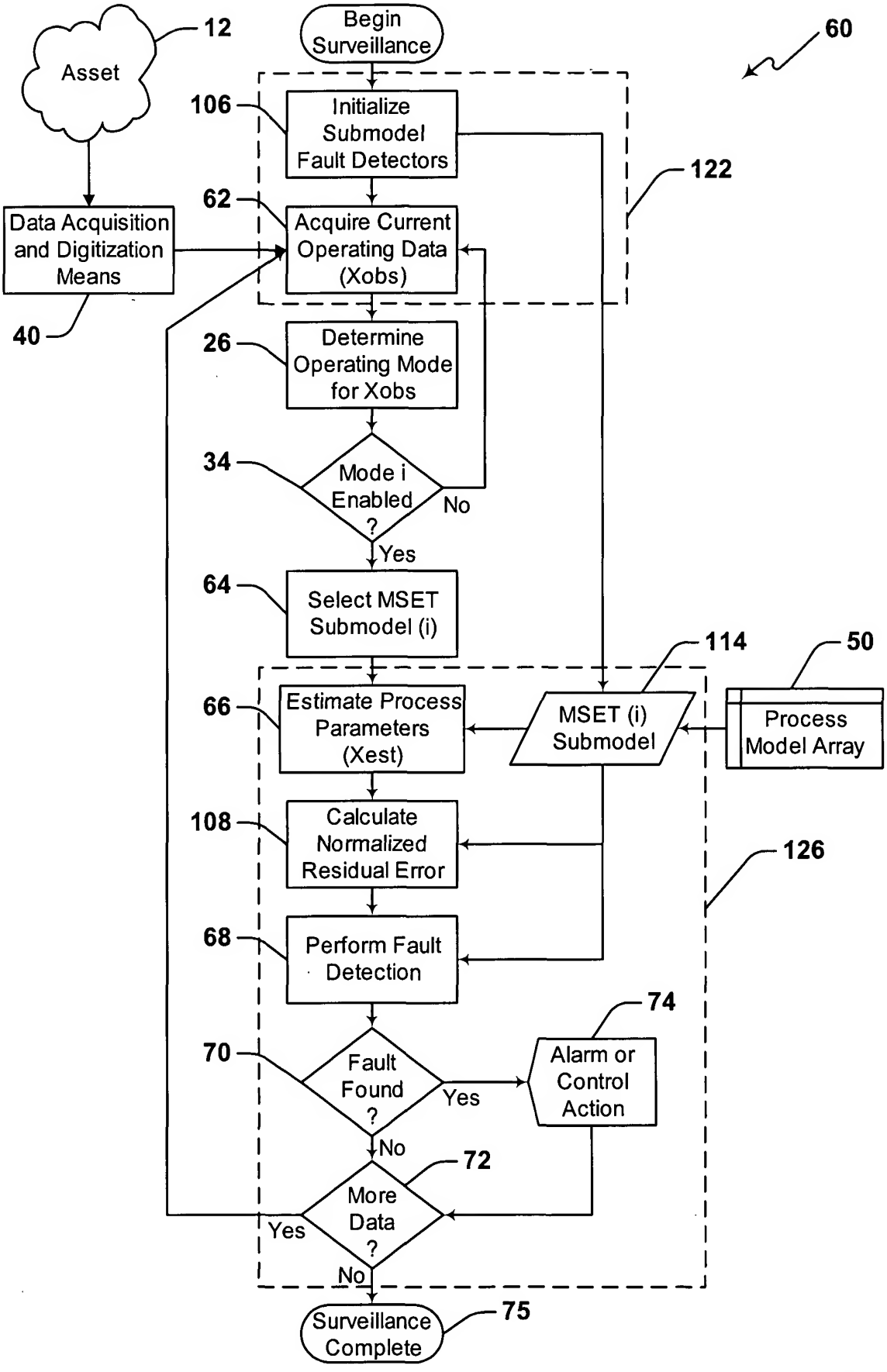
Asset
12
Begin Surveillance
60
106
Initialize Submodel Fault Detectors
122
62
Acquire Current Operating Data (Xobs)
Data Acquisition and Digitization Means
40
26
Determine Operating Mode for Xobs
34
Mode i Enabled ?
No
Yes
64
Select MSET Submodel (i)
114
50
66
Estimate Process Parameters (Xest)
MSET (i) Submodel
Process Model Array
108
Calculate Normalized Residual Error
126
68
Perform Fault Detection
74
70
Fault Found ?
Yes
Alarm or Control Action
No
72
More Data ?
Yes
No
Surveillance Complete
75

Figure 10

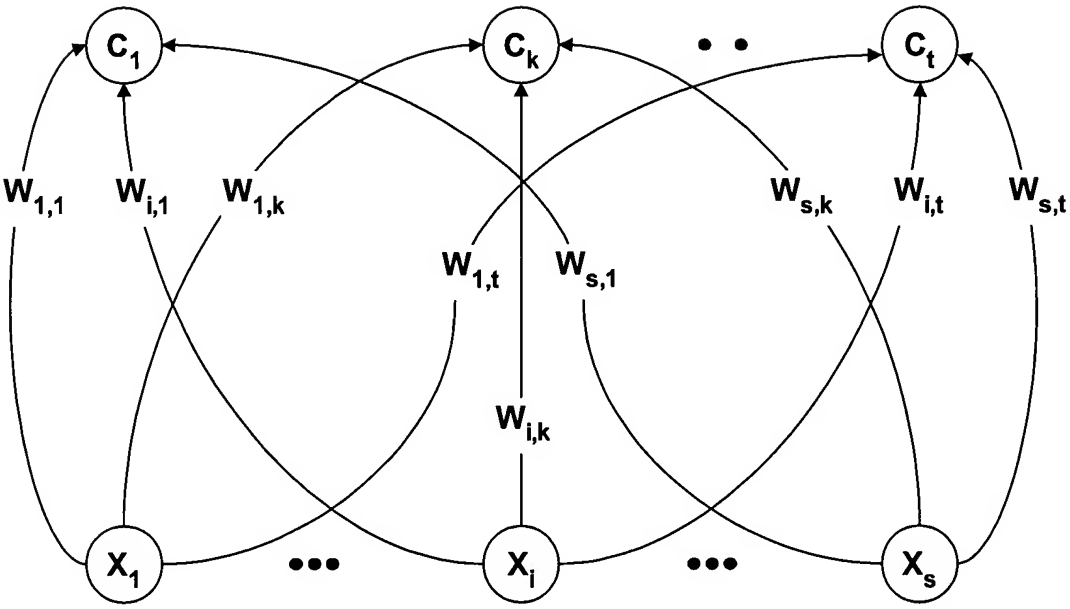

Figure 11

LVQ Neural Network Parameter	Design Value
Input Signals	MCC_PC_AVG (PC_CNTL_REF – MCC_PC_AVG) (ΔPC_CNTL_REF / ΔTIME)
Number of Classes	9 (one for each operating mode defined in Figure 16)
Number of Output Nodes per Class ($\mathbf{N_{class}}$)	8 (for each operating mode)
Learning Algorithm	LVQ2.1
Maximum Number of Epochs ($\mathbf{n_{eps}}$)	250
Initial Value of the Learning Rate (λ_0)	0.02
Window Size (ε)	0.5
Number of Training Vector Pairs ($\mathbf{n_{LVQ}}$)	500

Figure 12

SSME Signal Parameter ID	SSME Signal Parameter Name
PID40	OPOV_ACT_POS_A
PID42	FPOV_ACT_POS_A
PID52	HPFP_DS_P_A
PID58	FPB_PC_A
PID63	MCC_PC_AVG
PID90	HPOP_DS_P
PID100	FUEL_FLOW_AVG
PID105	HPFT_DS_T_A2
PID106	HPFT_DS_T_A3
PID107	HPFT_DS_T_B2
PID108	HPFT_DS_T_B3
PID200	MCC_PC_A_AVG
PID201	MCC_PC_B_AVG
PID205	HPOT_DS_T_A2
PID206	HPOT_DS_T_A3
PID207	HPOT_DS_T_B2
PID208	HPOT_DS_T_B3

Figure 13

Space Shuttle Flight ID	Engine Position
STS077	E2
STS078	E1
STS081	E3
STS082	E1
STS085	E1
STS085	E2
STS086	E2
STS087	E2
STS087	E3
STS090	E1

Figure 14

Model Description	Number of Signals	Modeled Operating Modes	Number of Process Mem Vectors	Parameter Estimation Method	Fault Detection Method
LVQ mode-partitioned (Model PD)	17 (defined in Figure 13)	Start01 Start12 Start24 SteadyFull SteadyLow Upthrust Downthrust	150 150 150 150 150 150 150	MSET / SSA	SPRT mean pos & neg
All-modes (Model A150)	17 (same)	All	150	MSET / SSA	SPRT mean pos & neg
All-modes (Model A300)	17 (same)	All	300	MSET / SSA	SPRT mean pos & neg

Figure 15

Mode Name	Operating Mode Criteria
PREFIRE	All observations preceding the vehicle start command to the engine. Considered a non-operating mode.
START01	Controller cycles 0 through 24 after receipt of the engine start command.
START12	Controller cycles 25 through 49 after receipt of the engine start command.
START24	Controller cycle 50 through detection of steady-state operation (typically at controller cycle ~110). The rule for transition to STEADY_FULL is: If in START24 and if |PC_CNTL_REF – MCC_PC_AVG | <= (5 * 3.35), and PC_CNTL_REF >= 2500 transition to STEADY_FULL
STEADY_FULL	STEADY_FULL is declared when either: 1) the last cycle's state was STEADY_FULL and the commanded PC is both unchanged and greater than 2500 psi, e.g., | PC_CNTL_REF –LAST_PC_CNTL_REF | < 3.35 and PC_CNTL_REF >= 2500; or 2) when the last cycle's state was a transient state and | PC_CNTL_REF – MCC_PC_AVG | <= (5 * 3.35) and PC_CNTL_REF >= 2500.
STEADY_LOW	STEADY_LOW is declared when either: 1) the last cycle's state was STEADY_LOW and the commanded PC is both unchanged and less than 2500 psi, e.g., | PC_CNTL_REF –LAST_PC_CNTL_REF | < 3.35 and PC_CNTL_REF < 2500; or 2) when the last cycle's state was a transient state and | PC_CNTL_REF – MCC_PC_AVG | <= (5 * 3.35) and PC_CNTL_REF < 2500.
UPTHRUST	UPTHRUST is declared when 1) the commanded PC has increased since the last cycle, and 2) | PC_CNTL_REF – MCC_PC_AVG | > (5 * 3.35)
DOWNTHRUST	DOWNTHRUST is declared when 1) the commanded PC has decreased since the last cycle, and 2) | PC_CNTL_REF – MCC_PC_AVG | > (5 * 3.35)
SHUTDOWN	All observations following the vehicle shutdown command to the engine. Considered a non-operating mode.

Figure 16

Test No.	Test Description	Sensor Failures	One Cycle Alarms	Total Avg Error %	Avg Cycle Time
PD-01	STS077E1. Nominal flight data.	0	2	0.408%	4.88 msec
PD-02	STS077E2. Nominal flight data.	0	0	0.217%	4.90 msec
PD-03	STS078E1. Nominal flight data.	0	0	0.352%	4.98 msec
PD-04	STS078E2. Nominal flight data.	0	1	0.296%	4.94 msec
PD-05	STS081E1. Nominal flight data.	0	2	0.400%	5.01 msec
PD-06	STS081E3. Nominal flight data.	0	0	0.281%	5.07 msec
PD-07	STS082E2. Nominal flight data.	0	1	0.286%	4.96 msec
PD-08	STS085E3. Nominal flight data.	0	0	0.282%	4.98 msec
PD-09	STS086E2. Nominal flight data.	0	0	0.254%	5.02 msec
PD-10	STS087E2. Nominal flight data.	0	0	0.246%	5.02 msec
Average for All Tests		*0*	*1*	*0.302%*	*4.98 msec*

Figure 17

Test No.	Test Description	Sensor Failures	One Cycle Alarms	Time to Detect	Error at Detect
PD-11	Drift PID40. 0.14 pct/sec beginning at 10.0 sec.	1 (PID40)	5	28.88 sec	5.8%
PD-12	Noise PID40. ±5 pct random beginning at 10.0 sec.	1 (PID40)	38	10.76 sec	N/A
PD-13	Drift PID42. 0.16 pct/sec beginning at 10.0 sec.	1 (PID42)	9	29.32 sec	5.9%
PD-14	Noise PID42. ±5 pct random beginning at 10.0 sec.	1 (PID42)	66	42.04 sec	N/A
PD-15	Drift PID52. 11.9 psi/sec beginning at 10.0 sec.	1 (PID52)	4	12.24 sec	2.4%
PD-16	Drift PID58. 10.2 psi/sec beginning at 10.0 sec.	1 (PID58)	5	9.44 sec	1.9%
PD-17	Drift PID90. 8.2 psi/sec beginning at 10.0 sec.	1 (PID90)	9	8.12 sec	1.6%
PD-18	Drift PID100. 31.9 gpm/sec beginning at 10.0 sec.	1 (PID100)	5	12.12 sec	2.4%
PD-19	Drift PID105. 3.4 degR/sec beginning at 10.0 sec.	1 (PID105)	11	16.16 sec	3.2%
PD-20	Drift PID200. 6.3 psi/sec beginning at 10.0 sec.	1 (PID200)	4	3.40 sec	0.7%
PD-21	Drift PID205. 2.7 degR/sec beginning at 10.0 sec.	1 (PID205)	4	18.28 sec	3.7%
Average for All Drift Tests				*15.3 sec*	*3.1%*

Figure 18

Test No.	Test D scription	S nsor Failures	On Cycle Alarms	Total Avg Error %	Avg Cycl Time
A150-01	STS077E1. Nominal flight data.	0	0	0.556%	5.27 msec
A150-02	STS077E2. Nominal flight data.	0	9	0.458%	5.28 msec
A150-03	STS078E1. Nominal flight data.	0	0	0.593%	4.90 msec
A150-04	STS078E2. Nominal flight data.	0	0	0.396%	5.28 msec
A150-05	STS081E1. Nominal flight data.	0	0	0.685%	4.67 msec
A150-06	STS081E3. Nominal flight data.	0	0	0.480%	4.77 msec
A150-07	STS082E2. Nominal flight data.	1 (PID58) False Alarm	13	0.720%	5.28 msec
A150-08	STS085E3. Nominal flight data.	0	0	0.519%	4.73 msec
A150-09	STS086E2. Nominal flight data.	0	0	0.410%	4.77 msec
A150-10	STS087E2. Nominal flight data.	0	0	0.399%	5.22 msec
Average for All Tests		*0*	*2*	*0.522%*	*5.02 msec*

Figure 19. Comparative Results

Test No.	Test Description	Sensor Failures	One Cycle Alarms	Time to Detect	Error at Detect
A150-11	Drift PID40. 0.14 pct/sec beginning at 10.0 sec.	1 (PID40)	19	125.68 sec	25.1%
A150-12	Noise PID40. ±5 pct random beginning at 10.0 sec.	1 (PID40)	12	95.04 sec	N/A
A150-13	Drift PID42. 0.16 pct/sec beginning at 10.0 sec.	1 (PID42)	12	154.92 sec	31.0%
A150-14	Noise PID42. ±5 pct random beginning at 10.0 sec.	0 (Missed Alarm)	0	Missed Alarm	N/A
A150-15	Drift PID52. 11.9 psi/sec beginning at 10.0 sec.	1 (PID52)	4	27.40 sec	5.5%
A150-16	Drift PID58. 10.2 psi/sec beginning at 10.0 sec.	1 (PID58)	6	18.92 sec	3.8%
A150-17	Drift PID90. 8.2 psi/sec beginning at 10.0 sec.	1 (PID90)	4	60.32 sec	12.1%
A150-18	Drift PID100. 31.9 gpm/sec beginning at 10.0 sec.	2 (PID100) & (PID58 False Alarm)	23	43.24 sec	8.6%
A150-19	Drift PID105. 3.4 degR/sec beginning at 10.0 sec.	1 (PID105)	10	46.20 sec	9.2%
A150-20	Drift PID200. 6.3 psi/sec beginning at 10.0 sec.	1 (PID200)	4	22.72 sec	4.5%
A150-21	Drift PID205. 2.7 degR/sec beginning at 10.0 sec.	1 (PID205)	8	89.04 sec	17.8%
	Average for All Drift Tests			*65.4 sec*	*13.1%*

Figure 20. Comparative Results

Test No.	Test Description	Sensor Failures	One Cycle Alarms	Total Avg Error %	Avg Cycle Time
A300-01	STS077E1. Nominal flight data.	0	0	0.488%	17.84 msec
A300-02	STS077E2. Nominal flight data.	0	0	0.379%	17.75 msec
A300-03	STS078E1. Nominal flight data.	0	0	0.424%	19.40 msec
A300-04	STS078E2. Nominal flight data.	0	0	0.359%	19.02 msec
A300-05	STS081E1. Nominal flight data.	0	0	0.633%	17.69 msec
A300-06	STS081E3. Nominal flight data.	0	0	0.501%	17.80 msec
A300-07	STS082E2. Nominal flight data.	0	0	0.620%	19.01 msec
A300-08	STS085E3. Nominal flight data.	0	2	0.521%	17.73 msec
A300-09	STS086E2. Nominal flight data.	0	1	0.340%	17.78 msec
A300-10	STS087E2. Nominal flight data.	0	0	0.319%	18.10 msec
Average for All Tests		*0*	*0*	*0.458%*	*18.21 msec*

Figure 21. Comparative Results

Test No.	Test Description	Sensor Failures	One Cycle Alarms[1]	Time to Detect	Error at Detect
A300-11	Drift PID40. 0.14 pct/sec beginning at 10.0 sec.	1 (PID40)	39	138.80 sec	27.8%
A300-12	Noise PID40. ±5 pct random beginning at 10.0 sec.	0 (Missed Alarm)	2	Missed Alarm	N/A
A300-13	Drift PID42. 0.16 pct/sec beginning at 10.0 sec.	1 (PID42)	26	139.08 sec	27.8%
A300-14	Noise PID42. ±5 pct random beginning at 10.0 sec.	0 (Missed Alarm)	2	Missed Alarm	N/A
A300-15	Drift PID52. 11.9 psi/sec beginning at 10.0 sec.	1 (PID52)	9	26.04 sec	5.2%
A300-16	Drift PID58. 10.2 psi/sec beginning at 10.0 sec.	1 (PID58)	8	16.92 sec	3.4%
A300-17	Drift PID90. 8.2 psi/sec beginning at 10.0 sec.	1 (PID90)	6	58.12 sec	11.6%
A300-18	Drift PID100. 31.9 gpm/sec beginning at 10.0 sec.	1 (PID100)	9	23.36 sec	4.7%
A300-19	Drift PID105. 3.4 degR/sec beginning at 10.0 sec.	1 (PID105)	6	28.32 sec	5.7%
A300-20	Drift PID200. 6.3 psi/sec beginning at 10.0 sec.	1 (PID200)	6	18.52 sec	3.7%
A300-21	Drift PID205. 2.7 degR/sec beginning at 10.0 sec.	1 (PID205)	12	64.32 sec	12.9%
	Average for All Drift Tests			*57.1 sec*	*11.4%*

Figure 22. Comparative Results

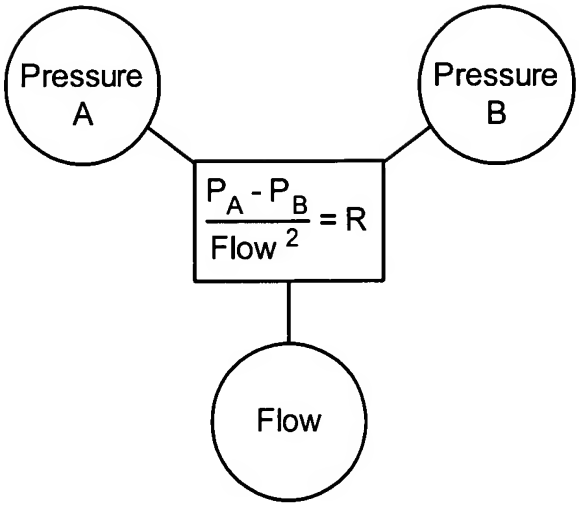

Figure 23